

# $B_s^0$ mixing and decays at the Tevatron

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This short review reports on recent results from CDF and DØ experiments at the Tevatron collider on  $B_s^0$  mixing and the lifetimes of  $B_s^0$  and  $\Lambda_b$ .

## 1. Introduction

Due to the large  $b\bar{b}$  cross section at 1.96 TeV  $p\bar{p}$  collisions, the Tevatron collider at Fermilab is currently the largest source of  $b$ -hadrons and provides a very rich environment for the study of  $b$ -hadrons. It is also the unique place to study high mass  $b$ -hadrons such as  $B_s^0$ ,  $B_c$ ,  $b$ -baryons and excited  $b$ -hadrons states.

CDF and DØ are both symmetric multipurpose detectors [1, 2]. They are essentially similar and consist of vertex detectors, high resolution tracking chambers in a magnetic field, finely segmented hermitic calorimeters and muons momentum spectrometers, both providing a good lepton identification. They have fast data acquisition systems with several levels of online triggers and filters and are able to trigger at the hardware level on large track impact parameters, enhancing the potential of their physics programs.

## 2. $B_s^0$ mixing

The  $B^0$ - $\bar{B}^0$  mixing is a well established phenomenon in particle physics. It proceeds via a flavor changing weak interaction in which the flavor eigenstates  $B^0$  and  $\bar{B}^0$  are quantum superpositions of the two mass eigenstates  $B_H$  and  $B_L$ . The probability for a  $B^0$  meson produced at time  $t = 0$  to decay as  $B^0$  or  $\bar{B}^0$  at proper time  $t > 0$  is an oscillatory function with a frequency  $\Delta m$ , the difference in mass between  $B_H$  and  $B_L$ . Oscillation in the  $B_d^0$  system is well established experimentally with a precisely measured oscillation frequency  $\Delta m_d$ . The world average value is  $\Delta m_d = 0.507 \pm 0.005 \text{ ps}^{-1}$  [3]. In the  $B_s^0$  system, the expected oscillation frequency value within the standard model (SM) is approximately 35 times faster than  $\Delta m_d$ . In the SM, the oscillation frequencies  $\Delta m_d$  and  $\Delta m_s$  are proportional to the fundamental CKM matrix elements  $|V_{td}|$  and  $|V_{ts}|$  respectively, and can be used to determine their values. This determination, however, has large theoretical uncertainties, but the combination of the  $\Delta m_s$  measurement with the precisely measured  $\Delta m_d$  allows the determination of the ratio  $|V_{td}|/|V_{ts}|$  with a significantly smaller theoretical uncertainty.

Both DØ and CDF have performed  $B_s^0$ - $\bar{B}_s^0$  mixing analysis using 1 fb $^{-1}$  of data [4, 5, 6]. The strategies used by the two experiments to measure  $\Delta m_s$  are very

similar. They schematically proceed as follows: the  $B_s^0$  decay is reconstructed in one side of the event and its flavor at decay time is determined from its decay products. The  $B_s^0$  proper decay time is measured from the difference between the  $B_s^0$  vertex and the primary vertex of the event. The  $B_s^0$  flavor at production time is determined from information in the opposite and/or the same-side of the event. finally,  $\Delta m_s$  is extracted from an unbinned maximum likelihood fit of mixed and unmixed events, which combines, among other information, the decay time, the decay time resolution and  $b$ -hadron flavor tagging. In the following only the latest CDF result is presented.

### 2.1. $B_s^0$ signal yields

The CDF experiment has reconstructed  $B_s^0$  events in both semileptonic  $B_s^0 \rightarrow D_s^{(*)-} \ell^+ \nu_\ell X$  ( $\ell = e$  or  $\mu$ ) and hadronic  $B_s^0 \rightarrow D_s^{*-} (\pi^+ \pi^-) \pi^+$  decays. In both cases the  $D_s^{*-}$  is reconstructed in the channels  $D_s^{*-} \rightarrow \phi \pi^-$ ,  $D_s^{*-} \rightarrow K^{*0} K^-$  and  $D_s^{*-} \rightarrow \pi^- \pi^+ \pi^-$  with  $\phi \rightarrow K^+ K^-$  and  $K^{*0} \rightarrow K^+ \pi^-$ . Additional partially reconstructed hadronic decays,  $B_s^0 \rightarrow D_s^{*-} \pi^+$  and  $B_s^0 \rightarrow D_s^{*-} \rho^+$  with unreconstructed  $\gamma$  and  $\pi^0$  in  $D_s^{*-} \rightarrow D_s^{*-} (\phi \pi^-) \gamma / \pi^0$  and  $\rho^+ \rightarrow \pi^+ \pi^0$  decay modes, have also been used. The signal yields are 61,500 semileptonic decays, 5,600 fully reconstructed and 3,100 partially reconstructed hadronic decays. This corresponds to an effective statistical increase in the number of reconstructed events of 2.5 compared to the first CDF published analysis [5]. This improvement was obtained mainly by using particle identification in the event selection, by using the artificial neural network (ANN) selection for hadronic modes and by loosening the kinematical selection. Figure 1 shows the distributions of the invariant masses of the  $D_s^{*-} (\phi \pi^-) \ell^+$  pairs  $m_{D_s \ell}$  and of the  $\bar{B}_s^0 \rightarrow D_s^{*-} (\phi \pi^+) \pi^-$  decays including the contributions from the partially reconstructed hadronic decays.

### 2.2. $B_s^0$ proper decay time reconstruction

The proper decay time of the reconstructed  $B_s^0$  events is determined from the transverse decay length  $L_{xy}$  which corresponds to the distance between the primary vertex and the reconstructed  $B_s^0$  vertex projected onto the transverse plane to the beam axis. For

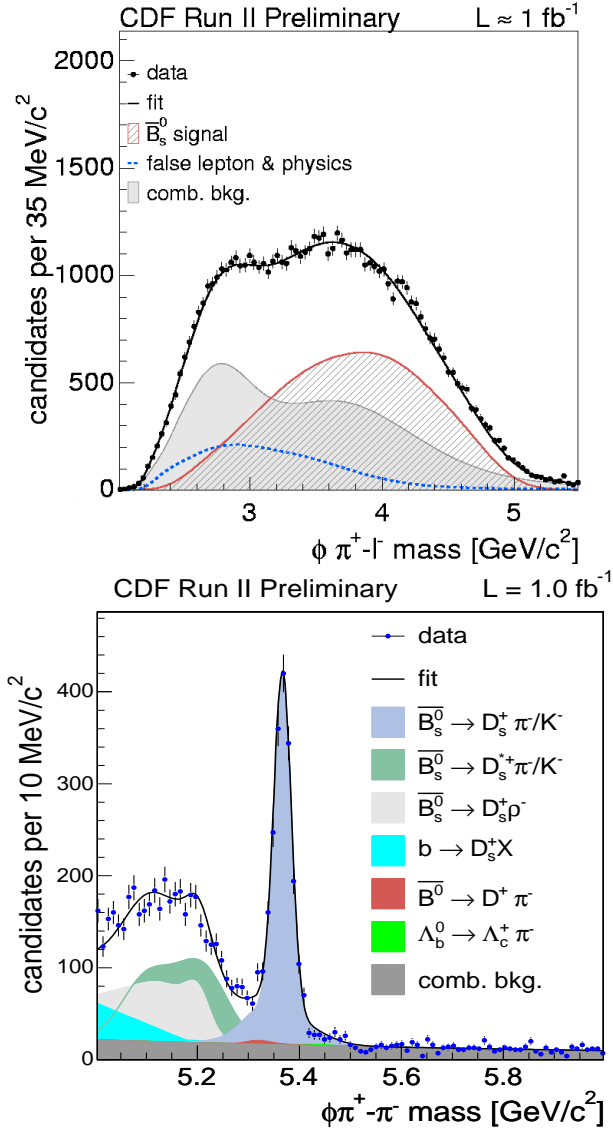


Figure 1: The invariant mass distributions for the  $D_s^+(\phi\pi^+)\ell^-$  pairs (upper plot) and for the  $\bar{B}_s^0 \rightarrow D_s^+(\phi\pi^+)\pi^-$  decays (bottom plot) including the contributions from the partially reconstructed hadronic decays.

the fully reconstructed  $B_s^0$  decay channels the proper decay time is well defined and is given by:

$$t = L_{xy} \frac{M(B_s^0)}{P_T(B_s^0)}$$

For the partially reconstructed  $B_s^0$  decay channels it is given by:

$$t = L_{xy} \frac{M(B_s^0)}{P_T(D_s \ell(\pi))} \times K, \quad K = \frac{P_T(D_s \ell(\pi))}{P_T(B_s^0)}$$

The  $K$ -factor takes into account the missing particles<sup>1</sup> in the event. It's distribution for different  $B_s^0$  decay channels is obtained from Monte Carlo simulation. For illustration, figure 2 shows the  $K$ -factor distributions obtained by CDF in semileptonic and partially reconstructed hadronic decays. The proper time resolution which is one of the critical parameters for  $\Delta m_s$  measurement, has contributions from the uncertainty on  $L_{xy}$  and from the momentum of the missing decay products. For the fully reconstructed decay modes, the mean proper decay time resolution obtained is 87 fs, which corresponds to the quarter of an oscillation period at  $\Delta m_s = 17.8 \text{ ps}^{-1}$ . For the partially reconstructed hadronic and semileptonic decays, the average proper decay time resolutions are  $\sigma_t = 97 \text{ fs}$  and  $\sigma_t = 168 \text{ fs}$  respectively.

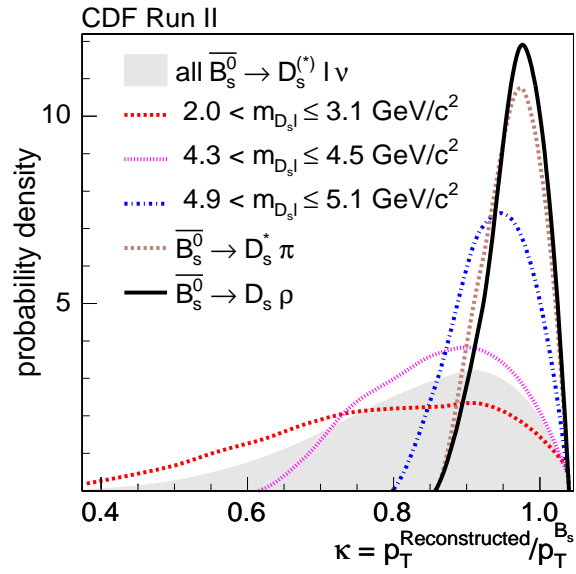


Figure 2: The distribution of the correction factor  $K$  in semileptonic and partially reconstructed hadronic decays from Monte Carlo simulation.

### 2.3. Flavor tagging

The flavor of the  $B_s^0$  at the decay time is determined precisely from its decay products. At production time, the flavor of the  $B_s^0$  is determined using both opposite-side and the same-side  $b$ -flavor tagging techniques. The opposite-side tagging exploits the fact that  $b$  quarks are dominantly produced in  $b\bar{b}$  pairs in hadron colliders. Same side tagging relies on the charges and the identity of associated particles produced in the fragmentation of the  $b$  quark that produces the reconstructed  $B_s^0$ . The effectiveness,  $Q \equiv \epsilon \mathcal{D}^2$ , of these techniques is quantified with

<sup>1</sup>Neutrino,  $\pi^0$  and  $\gamma$ .

an efficiency  $\epsilon$ , the fraction of signal candidates with a flavor tag, and a dilution  $\mathcal{D} = 1 - 2\omega$ , where  $\omega$  is the probability of mistagging.

The taggers used in the opposite-side of the event are the charge of the lepton ( $e$  and  $\mu$ ), the jet charge and the charge of identified kaons. The information from these taggers are combined in an ANN. The use of an ANN improves the combined opposite-side tag effectiveness by 20% ( $Q = 1.8 \pm 0.1\%$ ) compared to the previous analysis [5]. The dilution is measured in data using large samples of kinematically similar  $B_d^0$  and  $B^+$  decays.

The same-side flavor tags rely on the identification of the charge of the kaon produced from the left over  $\bar{s}$  in the process of  $B_s^0$  fragmentation. Any nearby charged particle to the reconstructed  $B_s^0$ , identified as a kaon, is expected to be correlated to the  $B_s^0$  flavor, with a  $K^+$  correlated to a  $B_s^0$  and  $K^-$  correlated to  $\bar{B}_s$ . An ANN is used to combine particle-identification likelihood based on information from the  $dE/dx$  and from the Time-of-Flight system, with kinematic quantities of the kaon candidate into a single variable. The dilution of the same side tag is estimated using Monte Carlo simulated data samples. The predicted effectiveness of the same-side flavor tag is  $Q=3.7\%$  (4.8%) in the hadronic (semileptonic) decay sample. The use of ANN increased the  $Q$  value by 10% compared to the previous analysis [5].

If both a same-side tag and an opposite-side tag are present, the information from both tags are combined assuming they are independent.

## 2.4. $\Delta m_s$ measurement

An unbinned maximum likelihood fit is used to search for  $B_s^0$  oscillations in the reconstructed  $B_s^0$  decays samples. The likelihood combines masses, decay time, decay-time resolution, and flavor tagging information for each reconstructed  $B_s^0$  candidate, and includes terms for signal and each type of background. The technique used to extract  $\Delta m_s$  from the unbinned maximum likelihood fit, is the amplitude scan method [7] which consists of multiplying the oscillation term of the signal probability density function in the likelihood by an amplitude  $\mathcal{A}$ , and fit its value for different  $\Delta m_s$  values. The oscillation amplitude is expected to be consistent with  $\mathcal{A} = 1$  when the probe value is the true oscillation frequency, and consistent with  $\mathcal{A} = 0$  when the probe value is far from the true oscillation frequency. Figure 3 shows the fitted value of the amplitude as function of the oscillation frequency for the combination of semileptonic and hadronic  $B_s^0$  candidates.

The sensitivity is  $31.3 \text{ ps}^{-1}$  for the combination<sup>2</sup>

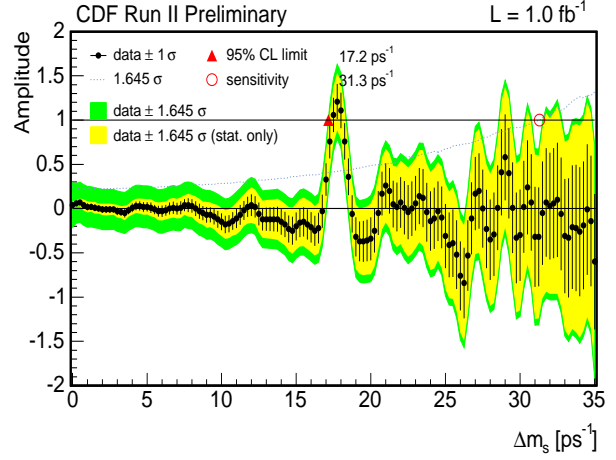


Figure 3: The measured amplitude values and uncertainties versus the  $B_s^0$ - $\bar{B}_s^0$  oscillation frequency  $\Delta m_s$ .

of all hadronic and semileptonic decay modes. At  $\Delta m_s = 17.75 \text{ ps}^{-1}$ , the observed amplitude  $\mathcal{A} = 1.21 \pm 0.20$  (stat.) is consistent with unity and  $\mathcal{A}/\sigma_{\mathcal{A}} = 6.05$  where  $\sigma_{\mathcal{A}}$  is the statistical uncertainty on  $\mathcal{A}$ . This shows that the amplitude is inconsistent with zero and that the data are compatible with  $B_s^0$ - $\bar{B}_s^0$  oscillations with that frequency. The significance of the signal is evaluated using the logarithm likelihood ratio  $\Lambda \equiv \log [\mathcal{L}^{\mathcal{A}=0}/\mathcal{L}^{\mathcal{A}=1}(\Delta m_s)]$ . Figure 4 shows  $\Lambda$  as function of  $\Delta m_s$ . At the minimum  $\Delta m_s = 17.77 \text{ ps}^{-1}$ ,  $\Lambda = -17.26$ . The significance of the signal is the probability that randomly tagged data would produce a value of  $\Lambda$  lower than -17.26 at any  $\Delta m_s$  value. This probability has been determined to be  $8 \times 10^{-8}$  which corresponds to a significance of  $5.4 \sigma$ .

The  $\Delta m_s$  value is determined from the fit for oscillation frequency at amplitude value  $\mathcal{A} = 1$ . The fit result is  $\Delta m_s = 17.77 \pm 0.10$  (stat.)  $\pm 0.07$  (sys.)  $\text{ps}^{-1}$ . The systematic error is completely dominated by the time scale uncertainty.

The measured  $B_s^0$ - $\bar{B}_s^0$  oscillation frequency is used to determine the ratio  $|V_{td}/V_{ts}|$ . If one uses as inputs  $m_{B_d^0}/m_{B_s^0} = 0.98390$  [8] with negligible uncertainty,  $\Delta m_d = 0.507 \pm 0.005 \text{ ps}^{-1}$  [3] and  $\xi = 1.21_{-0.035}^{+0.047}$  [9], one finds:

$$\begin{aligned} |V_{td}/V_{ts}| &= \xi \sqrt{\frac{\Delta m_d m_{B_s^0}}{\Delta m_s m_{B_d^0}}} \\ &= 0.2060 \pm 0.0007 (\text{exp})_{-0.006}^{+0.0081} (\text{theor}) \end{aligned}$$

<sup>2</sup>19.3  $\text{ps}^{-1}$  for the semileptonic decays alone and 30.7  $\text{ps}^{-1}$

for the hadronic decays alone.

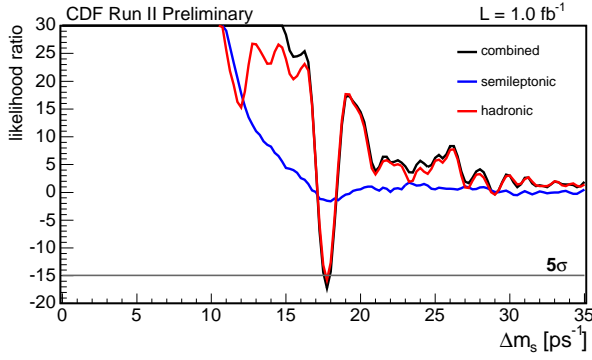


Figure 4: The logarithm of the ratio of likelihoods  $\Lambda \equiv \log [\mathcal{L}^{A=0}/\mathcal{L}^{A=1}(\Delta m_s)]$ , versus the oscillation frequency. The horizontal line indicates the value  $\Lambda = -15$  that corresponds to a probability of  $5.7 \times 10^{-7}$  ( $5\sigma$ ) in the case of randomly tagged data.

### 3. $b$ -hadrons lifetime measurements at the Tevatron RunII

Lifetime measurements of  $b$ -hadrons provide important information on the interactions between heavy and light quarks. These interactions are responsible for lifetime hierarchy among  $b$ -hadrons observed experimentally:

$$\tau(B^+) \geq \tau(B_d^0) \simeq \tau(B_s^0) > \tau(\Lambda_b) \gg \tau(B_c)$$

Currently most of the theoretical calculations of the light quark effects on  $b$  hadrons lifetimes are performed in the framework of the Heavy Quark Expansion (HQE) [10] in which the decay rate of heavy hadron to an inclusive final state  $f$  is expressed as an expansion in  $\Lambda_{\text{QCD}}/m_b$ . At leading order of the expansion, light quarks are considered as spectators and all  $b$  hadrons have the same lifetime. Differences between meson and baryon lifetimes arise at  $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_b^2)$  and splitting of the meson lifetimes appears at  $\mathcal{O}(\Lambda_{\text{QCD}}^3/m_b^3)$ .

Both CDF and DØ have performed a number of  $b$ -hadrons lifetimes measurements for all  $b$ -hadrons species. Most of these measurements are already included in the world averages and are summarised in [11]. In this note focus will be on the latest results on  $B_s^0$  and  $\Lambda_b$  measurements from CDF and DØ.

#### 3.1. $B_s^0$ lifetime measurements

In the standard model the light  $B_L$  and the heavy  $B_H$  mass eigenstates of the mixed  $B_s^0$  system are expected to have a sizeable decay width difference of order  $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.096 \pm 0.039 \text{ ps}^{-1}$  [12]. If CP violation is neglected, the two  $B_s^0$  mass eigenstates are expected to be CP eigenstates, with  $B_L$  being the CP even state and  $B_H$  being the CP odd state.

Various  $B_s^0$  decay channels have a different proportion of  $B_L$  and  $B_H$  eigenstates:

- Flavor specific decays, such as  $B_s^0 \rightarrow D_s^+ \ell^- \bar{\nu}_\ell$  and  $B_s^0 \rightarrow D_s^+ \pi^-$  have equal fractions of  $B_L$  and  $B_H$  at  $t = 0$ . The fit to the proper decay length distributions of these decays with a single signal exponential lead to a flavor specific lifetime:

$$\tau_{B_s}(fs) = \frac{1}{\Gamma_s} \frac{1 + \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1 - \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}, \quad \Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

- Fully exclusive  $B_s^0 \rightarrow J/\psi\phi$  decays are expected to be dominated by CP even state and its lifetime.

##### 3.1.1. $B_s^0$ lifetime measurements in flavor specific modes

Both CDF and DØ have measured  $B_s^0$  lifetime in the semileptonic decays  $B_s^0 \rightarrow D_s^+ \ell^- \bar{\nu}_\ell$ . Results based on respectively 360 and 400  $\text{pb}^{-1}$  were presented at the FPCP06 conference last year [13, 14]. These are:

$$\begin{aligned} \tau_{B_s^0}^{\text{DØ}}(fs) &= 1.398 \pm 0.044(\text{stat})_{-0.025}^{+0.028}(\text{sys}) \text{ ps} \\ \tau_{B_s^0}^{\text{CDF}}(fs) &= 1.381 \pm 0.055(\text{stat})_{-0.046}^{+0.052}(\text{sys}) \text{ ps}. \end{aligned}$$

The DØ measurement provides the world best  $B_s^0$  lifetimes measurement in the flavor specific decays.

CDF has also measured  $B_s^0$  lifetime in the fully hadronic modes,  $B_s^0 \rightarrow D_s^+ \pi^-$  and  $B_s^0 \rightarrow D_s^+ \pi^+ \pi^- \pi^-$ . To date the analysis is based only on 360  $\text{pb}^{-1}$ . The  $B_s^0$  lifetime is extracted from a simultaneous fit to the mass and decay length distributions of the two decay modes. Figure 5 shows the distribution of the proper decay length and fits to the  $B_s^0$  candidates. The measured  $B_s^0$  lifetime is [15]  $\tau_{B_s^0}^{\text{CDF}} = 1.60 \pm 0.10(\text{stat}) \pm 0.02(\text{sys}) \text{ ps}$ . These measurements in the semileptonic and the hadronic decay modes will soon be updated with 1  $\text{fb}^{-1}$  of data.

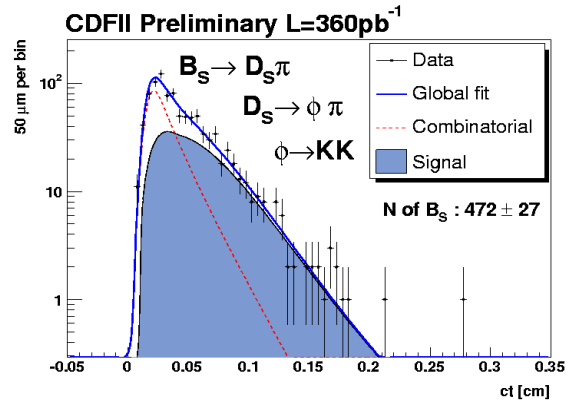


Figure 5: Proper decay length distribution of the  $B_s^0$  candidates, with the fit result superimposed. The shaded region represents the signal.

### 3.1.2. $B_s^0$ lifetime measurements in $B_s^0 \rightarrow J/\psi\phi$

DØ experiment has performed a new  $B_s^0$  mean lifetime measurement in  $B_s^0 \rightarrow J/\psi\phi$  decay mode. The analysis uses a data set of  $1.1 \text{ fb}^{-1}$  and extracts three parameters, the average  $B_s^0$  lifetime  $\bar{\tau}(B_s^0) = 1/\Gamma_s$ , the width difference between the  $B_s^0$  mass eigenstates  $\Delta\Gamma_s$  and the CP-violating phase  $\phi_s$ , through a study of time-dependent angular distribution of the decay products of the  $J/\psi$  and  $\phi$  mesons. Figure 6 shows the distribution of the proper decay length and fits to the  $B_s^0$  candidates. From a fit to the CP-conserving time-dependent angular distributions of untagged decay  $B_s^0 \rightarrow J/\psi\phi$ , the measured values of the average lifetime of the  $B_s^0$  system and the width difference between the two  $B_s^0$  mass eigenstates are [16]:

$$\begin{aligned}\tau_{B_s^0}^{\text{DØ}} &= 1.52 \pm 0.08(\text{stat})^{+0.01}_{-0.03}(\text{sys}) \text{ ps} \\ \Delta\Gamma_s &= 0.12^{+0.08}_{-0.10}(\text{stat}) \pm 0.02(\text{sys}) \text{ ps}^{-1}\end{aligned}$$

Allowing for CP-violation in  $B_s^0$  mixing, DØ provides

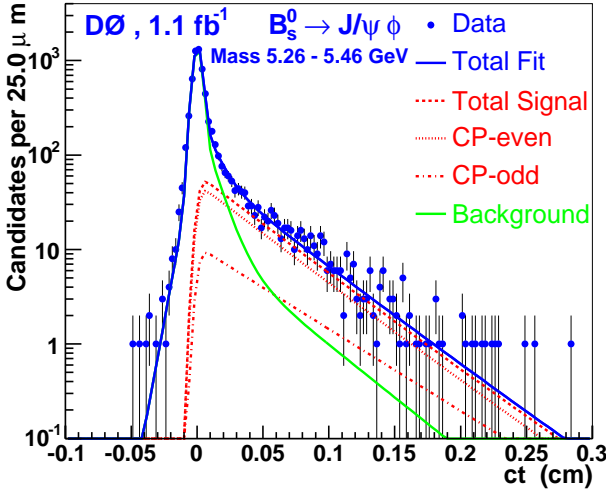


Figure 6: The proper decay length,  $ct$ , of the  $B_s^0$  candidates in the signal mass region. The curves show: the signal contribution, dashed (red); the CP-even (dotted) and CP-odd (dashed-dotted) contributions of the signal, the background, light solid (green); and total, solid (blue).

the first direct constraint on the CP-violating phase,  $\phi_s = -0.79 \pm 0.56(\text{stat})^{+0.14}_{-0.01}(\text{sys})$ , value compatible with the standard model expectations.

### 3.2. $\Lambda_b$ lifetime measurements

Both CDF and DØ have measured the  $\Lambda_b$  lifetime in the golden decay mode  $\Lambda_b \rightarrow J/\psi\Lambda$ . Similar analysis procedure have been used by the two experiments, on respectively 1 and  $1.2 \text{ fb}^{-1}$  of data. The  $\Lambda_b$  lifetime

was extracted from an unbinned simultaneous likelihood fit to the mass and proper decay lengths distributions. To cross check the validity of the method similar analysis were performed on the kinematically similar decay  $B^0 \rightarrow J/\psi K_s$ . Figure 7 shows the proper decay time distributions of the  $J/\psi\Lambda$  pair samples from CDF and DØ. The  $\Lambda_b$  lifetime values extracted from the maximum likelihood fit to these distributions are [17, 18]:  $\tau_{\Lambda_b}^{\text{CDF}} = 1.580 \pm 0.077(\text{stat}) \pm 0.012(\text{sys})$  ps and  $\tau_{\Lambda_b}^{\text{DØ}} = 1.218^{+0.130}_{-0.115}(\text{stat}) \pm 0.042(\text{sys})$  ps.

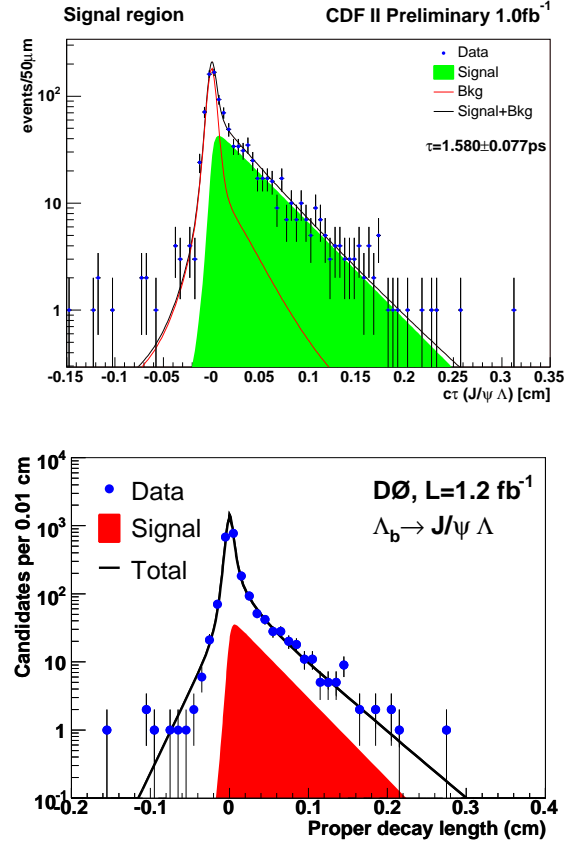


Figure 7: Proper decay length distribution of the  $\Lambda_b$  candidates from CDF (upper plot) and DØ (bottom plot), with the fit result superimposed. The shaded regions represent the signal.

The CDF measured value is the single most precise measurement of the  $\Lambda_b$  lifetime but is  $3.2 \sigma$  higher than the current world average [3] ( $\tau_{\Lambda_b}^{\text{W.A.}} = 1.230 \pm 0.074$  ps). The DØ result however is consistent with the world average value. The CDF and DØ  $B^0 \rightarrow J/\psi K_s$  measured lifetimes are:  $\tau_{B^0}^{\text{CDF}} = 1.551 \pm 0.019(\text{stat}) \pm 0.011(\text{sys})$  ps and  $\tau_{B^0}^{\text{DØ}} = 1.501^{+0.078}_{-0.074}(\text{stat}) \pm 0.05(\text{sys})$  ps. Both are compatible with the world average value [11] ( $\tau_{B^0}^{\text{W.A.}} = 1.527 \pm 0.008$  ps). One needs more experimental input to conclude about the difference between the CDF and the DØ/world average  $\Lambda_b$  lifetime values. One of the  $\Lambda_b$  decay modes that can be exploited is the fully



hadronic  $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ , with  $\Lambda_c^+ \rightarrow p K^- \pi^+$ . CDF has in this decay mode about 3000 reconstructed events which is 5.6 more than in  $\Lambda_b \rightarrow J/\psi \Lambda$ .

Recently, the DØ experiment has performed a new measurement of the  $\Lambda_b$  lifetime in the semileptonic decay channel  $\Lambda_b \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu X$ , with  $\Lambda_c^+ \rightarrow K_s p$  [19]. This measurement is based on  $1.2 \text{ fb}^{-1}$  of data. As this is a partially reconstructed decay mode the proper decay time is corrected by a kinematical factor  $K = P_T(\Lambda_c^+ \mu^-)/P_T(\Lambda_b)$ , estimated from Monte Carlo simulation. The  $\Lambda_b$  lifetime is not determined from the usually performed unbinned maximum likelihood fit, but is extracted from the number of  $K_s p \mu^-$  events in bins of their visible proper decay length (VPDL). Figure 8 shows the distribution of the number of  $\Lambda_c^+ \mu^-$  as function of the VPDL with the result of the fit superimposed. The fitted  $\Lambda_b$  lifetime value is  $\tau(\Lambda_b) = 1.28 \pm 0.12(\text{stat}) \pm 0.09(\text{sys})$  ps. This results is compatible with the lifetime value from  $\Lambda_b \rightarrow J/\psi \Lambda$  and the world average.

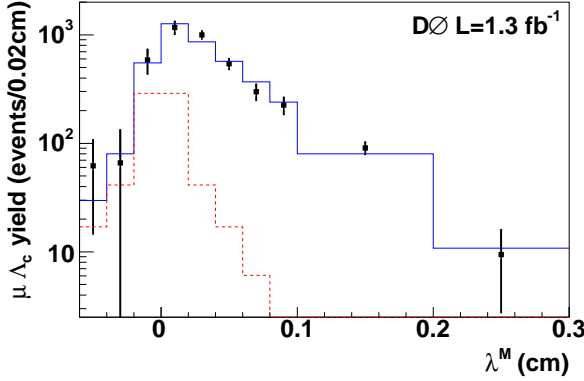


Figure 8: Measured yields in the VPDL bins and the result of the lifetime fit. The dashed line shows the  $c\bar{c}$  contribution.

## Acknowledgments

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